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Frequency Screening of First Stage Turbine Blades in the T56-A-7B Engine (U)

Andrew Becker and
Paul Marsden

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Frequency Screening of First Stage Turbine Blades in the T56-A-7B Engine

Andrew Becker and Paul Marsden

Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

DSTO-TN-0223

ABSTRACT

Historically it has been difficult to obtain accurate and repeatable frequency data for the first bending mode of turbine blades. This report summarises the technique used by AMRL to screen first stage T56-A-7B turbine blades for the Royal Australian Air Force as part of an investigation into the failure of these blades in service.

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Frequency Screening of First Stage Turbine Blades in the T56-A-7B Engine

Executive Summary

This report describes the technique used by AMRL to frequency screen T56-A-7B engine first stage turbine blades. The C130E Hercules aircraft operated by the Royal Australian Air Force (RAAF) are fitted with these engines which are manufactured by Rolls-Royce Allison (RRA). Due to an unexplained increase in the number of first stage turbine blade failures, AMRL was asked to contribute to an investigation which included the frequency screening of all new blades prior to installation and the development of a screening technique to be used by Qantas (the engine overhaul contractor).

RRA suggested that the most likely cause of the blade failures was a drop in natural frequency which then allowed the blade to be excited by the seventh engine order vibration (1612 Hz). RRA claimed that all new blades should have a first bending mode (1B or cantilever mode) frequency above 1850 Hz at room temperature and with no centrifugal loading.

The RAAF stipulated that all new blades fitted to overhauled turbines must be frequency screened prior to installation. A delay in correlating the AMRL technique with the RRA technique coupled with the RAAF screening proviso meant that any blades found to have a suspect frequency were kept by AMRL and tested later in the correlated apparatus.

A new clamping technique was developed by AMRL to enable repeatable and accurate frequency data to be recorded. Frequency data was recorded for both the first bending mode (1B or cantilever mode) and the first free-free mode (blade unrestrained at both ends). Initially it was thought that a relationship existed between the 1B and free-free modes, however this proved to be incorrect.

During the screening of approximately 2000 new blades, a double peak phenomenon was recorded for a large number of blades. When observed in the frequency domain of the Fast Fourier Transform analyser, these blades displayed two peaks at approximately 50 Hz apart with similar amplitudes. No adequate explanation of this phenomenon was concluded, however it was not a significant factor in the screening process.

It had been suggested by RRA that untwist of the blade due to creep in service may contribute to the high failure rate by lowering the blades natural frequency into the seventh engine order range. Life expired blades (containing some inherent untwist)

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1. Introduction

The purpose of this report is to describe the technique developed by the Aeronautical and Maritime Research Laboratory (AMRL) for frequency screening first stage turbine blades in the T56-A-7B engine. AMRL were asked to contribute to an investigation into the increased failure rate of first stage turbine blades by high cycle fatigue (HCF) in the T56-A-7B engine. This engine is manufactured by Rolls-Royce Allison (RRA) and is fitted to the C130E Hercules fleet operated by the Royal Australian Air Force (RAAF). Prior to 1997, the RAAF experienced an average of 1.5–2 first stage turbine blade failures per year. In 1997 this increased to five followed by eight failures in 1998 [1].

Obtaining repeatable and accurate frequency data for turbine blades is notoriously difficult primarily due to the difficulties associated with clamping the fir tree part of the blade as a rigid mount. Further to this, the significance of laboratory testing could be questioned considering the vastly different environment in which the blade operates when installed in the turbine. The estimated effects of both temperature and centrifugal force on blade natural frequency were provided by RRA for this investigation.

RRA suggested that it was likely that the failed blades were excited into resonance by the seventh engine order vibration (1612 Hz); this resonance then initiated a crack in the fir tree region that ultimately caused failure of the blade by HCF. One aspect of AMRL's contribution was to investigate the natural frequency of first stage turbine blades in the first bending mode (1B or cantilever mode). RRA claimed that all new blades should have a 1B natural frequency above 1850 Hz at ambient temperature and with no centrifugal load. They also stated that the combined effects of centrifugal loading and operating temperature would give a net increase of approximately 60 Hz to the 1B natural frequency recorded in the laboratory [2]. The Airframes and Engines Division (AED) of AMRL were tasked with frequency screening new blades prior to installation as well as the development of a pre-installation frequency screening technique for use by Qantas who is the T56 overhaul contractor.

2. Testing Methods

2.1 Rolls-Royce Allison Method

2.1.1 Clamping

Initially, AED attempted to replicate the frequency testing technique used by RRA. The technique used by RRA involved placing the blade in a coupon that matched the fir tree shape and then clamping the complete assembly in a vice. Additionally, a load-sharing pin was placed in the vice in order to correct any jaw skewing arising from the off-centre loading (Figure 1).

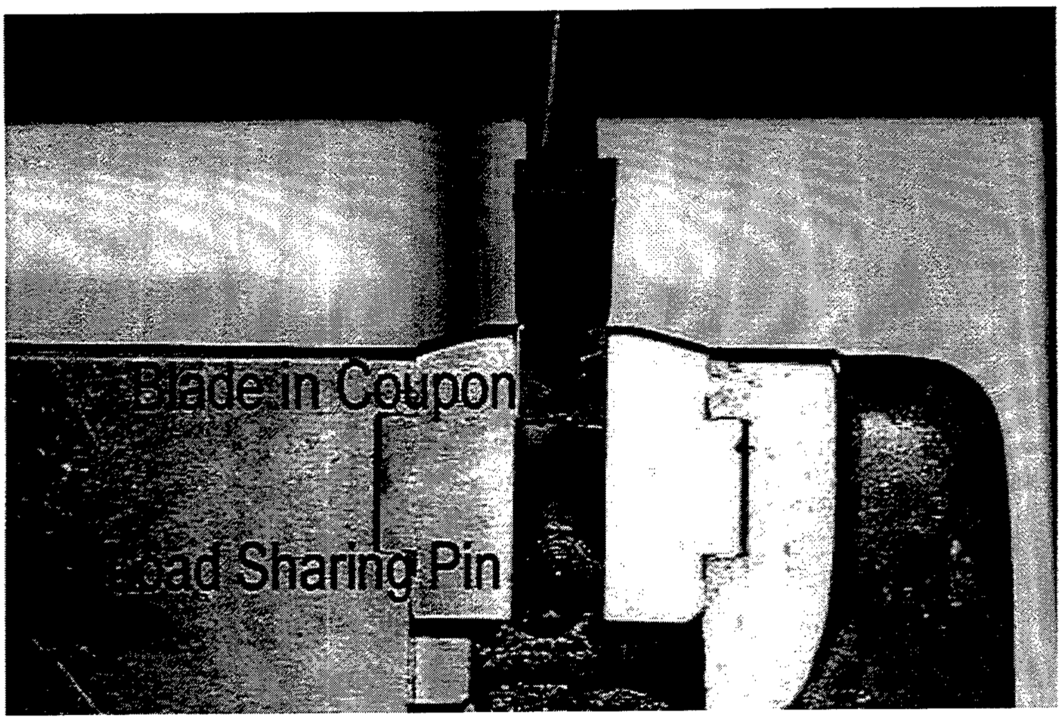

Figure 1. RRA load sharing pin arrangement

According to RRA, 1B frequency is maximised for the first blade in a batch by altering the diameter of the load sharing pin; this set up then remains unaltered for the remainder of the batch [3]. RRA alter the pin diameter by using a variety of pins of fractionally different diameter until the maximum frequency is observed. AMRL altered the effective diameter of the pin by including shim metal.

This approach was trialed during the initial testing of new blades for the RAAF. The load-sharing pin, however, was found to be unnecessary in the AMRL machine vice as the blade frequency appeared to be maximised before the pin took effect. Figure 2

illustrates how the test blade frequency altered with changing diameter of load sharing pin for the AMRL machine vice.

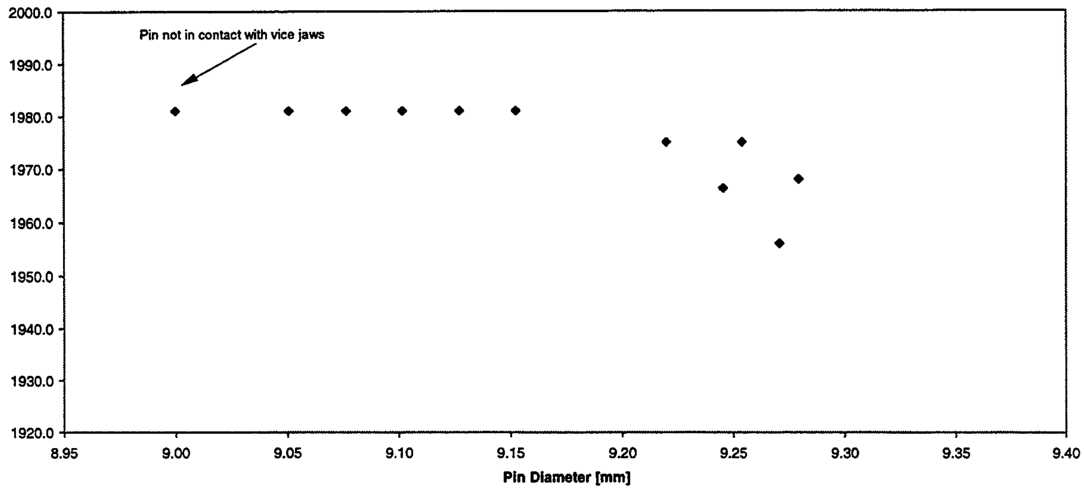

Figure 2. Effect of load sharing pin on blade 1B frequency

2.1.2 Excitation and Data Collection

Once the blade had been clamped in position, it was excited by sound waves produced by a generator and focused onto the blade by a short length of tube. An eddy current proximity probe was placed on the reverse side of the blade in order to detect the 1B frequency.

2.2 AMRL Method

2.2.1 Method

As certain detailed aspects of the RRA testing method did not become apparent until well into the testing program, it was decided to devise an independent testing method that would be correlated with the RRA method. Each blade was clamped with a predetermined force and then struck with a light impact hammer to determine the 1B frequency. The blade was then released, re-clamped and re-tested a further three times giving a total of four 1B frequency readings for each blade. The reason for acquiring multiple readings for each blade was to average out any inconsistencies with clamping or excitation.

2.2.2 Vice Selection

A rigidly mounted vice was essential for obtaining repeatable data. Initially a number of machine vices were trialed with various degrees of repeatability. At this stage the blade and coupon assembly were clamped in the uppermost section of the jaw in a similar fashion to the RRA method described above. A height gauge was also used to ensure all blades were being clamped at the same location. It soon became evident that to expedite the screening process, a custom made jaw would have to be manufactured. This would allow the blade/coupon assembly to be clamped in line with the applied load thus alleviating any jaw skewing. The vice finally selected was a hydraulic self centring vice manufactured by Enerpac (see Section 2.4).

2.2.3 Clamping Force

Clamping force is the force required to hold the blade rigidly at one end in the vice whilst not causing damage at the fir tree of the blade. Initially RRA suggested that a clamping force within the range of 15.5–17.8kN (3500–4000lbf) would be adequate to hold the blade. Later this was revised by RRA to a range of 20–22.2kN (4500–5000lbf) [4]. As this load appeared to be high, given the small contact area at the fir tree, a Finite Element (FE) model developed by AMRL [5] was used to determine whether damage to the fir tree region of the blade would occur. The FE model revealed that if the higher clamping load range was used, compressive yield would take place in the fir tree region.

A further investigation was carried out by grinding and then polishing a life expired blade perpendicular to the applied force. A photograph was taken of the blade following clamping at the elevated force which revealed compressive yielding in the fir tree region. These two investigations led to the higher clamping force being rejected for new blades. It was subsequently revealed that this higher force was not the force felt by the blade in the RRA testing set up. A load sharing pin inserted in the vice resulted in approximately two thirds of the applied load being felt by the blade being tested [6]. The final clamping force range chosen for AMRL testing was therefore 13–15kN.

Additionally, a sensitivity check was conducted to see how the 1B frequency was effected by clamping force (Figure 3). This check revealed that there was only minor variation in frequency as the clamping load was increased. It should be noted that at clamping loads below those shown, the 1B frequency was no longer clearly distinguishable on the Fast Fourier Transform (FFT) analyser.

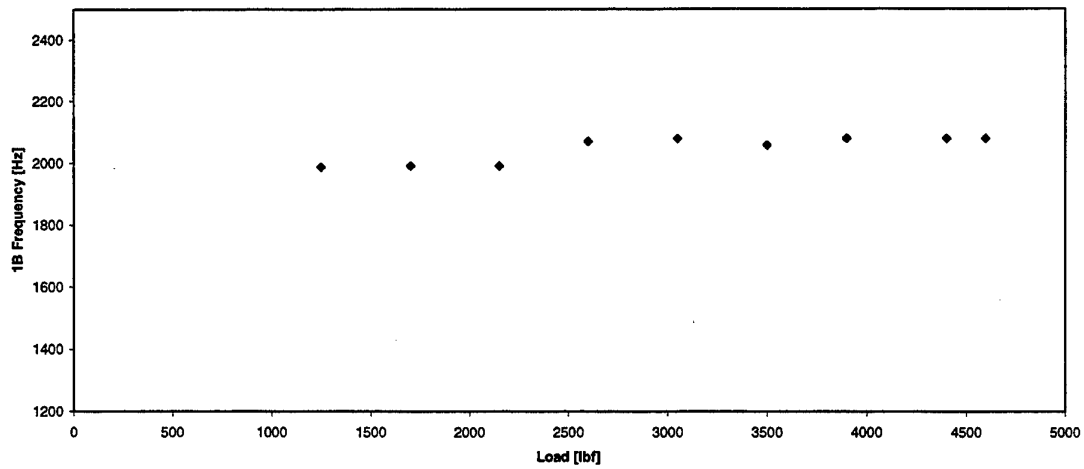

Figure 3. 1B Frequency sensitivity to clamping force

2.2.4 Excitation and Data Collection

Once the blade had been mounted in the coupon and clamped in the vice with the required force, it was excited by a light impact hammer made of plastic. A variety of hammers were trialed including a small brass hammer and a metal hammer encased in heat shrink plastic; the plastic hammer which was nothing more than a pen casing, provided the best results. An eddy current proximity probe was placed near the blade and connected to a FFT analyser in order to detect and record the transient response of the blade. The main concern about this type of excitation was the possibility of causing impact damage to new blades. Other methods of excitation such as compressed air and sound were trialed briefly, however neither gave results that were as clear or repeatable as the impact hammer. Additionally, the RAAF were keen to commence frequency screening blades as soon as possible which meant further excitation trials could not be accommodated. A light tap from the plastic hammer provided sufficient excitation of the blade without causing any blade damage.

2.3 Testing Method Correlation

Before the frequency screening technique could be implemented at Qantas, the data obtained at AMRL needed to be correlated with that obtained by RRA. RRA stated that all new blades should have a 1B natural frequency above 1850 Hz when tested in the laboratory. Initial testing by AMRL appeared to reveal several blades that exhibited frequencies significantly lower than the minimum claimed by RRA (Figure 4). More importantly, these blades appeared to have frequencies very close to the seventh

engine order. The entire set of 109 blades were sent to RRA for correlation which revealed a significant discrepancy between the AMRL frequency data and that obtained by RRA. Specifically, blades 12, 45, 58 and 59 appeared to have low frequencies when tested by AMRL and satisfactory frequencies when tested by RRA. Also, there appeared to be a 200 Hz discrepancy between the mean for each data set. It was thought that there may have been a problem with the clamping arrangement so a new coupon was made at AMRL from blade material.

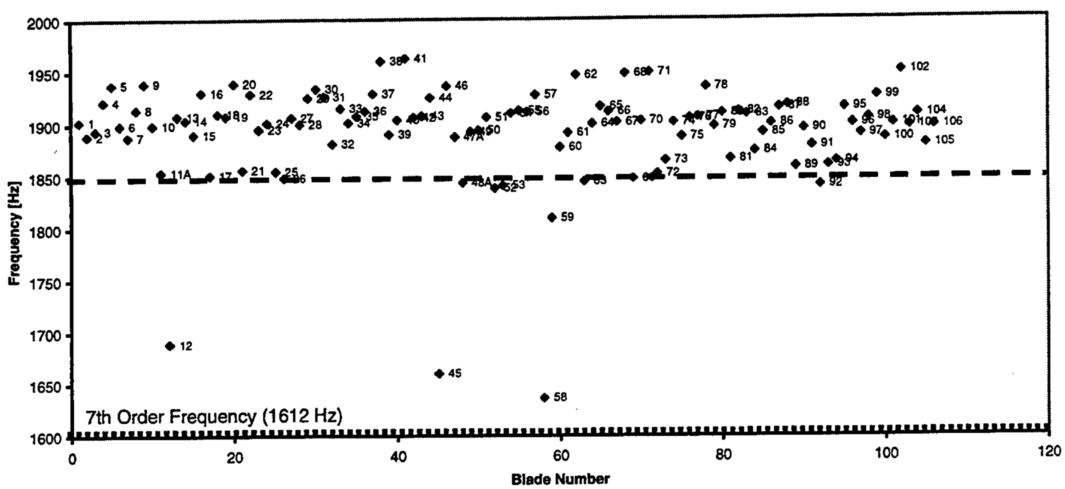

Figure 4. Initial AMRL 1B frequency results

RRA had suggested that the vice initially used by AMRL was too light and may have effected the frequencies recorded [7]. A larger and heavier machine vice was acquired and this combined with the new coupon appeared to account for the majority of the 200 Hz difference. Unfortunately this vice could not be correlated using the initial 109 blades as they were detained for an extended period in the United States of America under a trade regulation.

By the time the 109 blades were released and returned to AMRL, a new hydraulic vice (described in Section 3) had been constructed and was in use. Figure 5 shows the correlation between the RRA frequency data for the 109 correlation blades, and the AMRL hydraulic vice frequency data. As both data sets followed very similar trends, the correlation was considered acceptable despite the apparent 50 Hz shift.

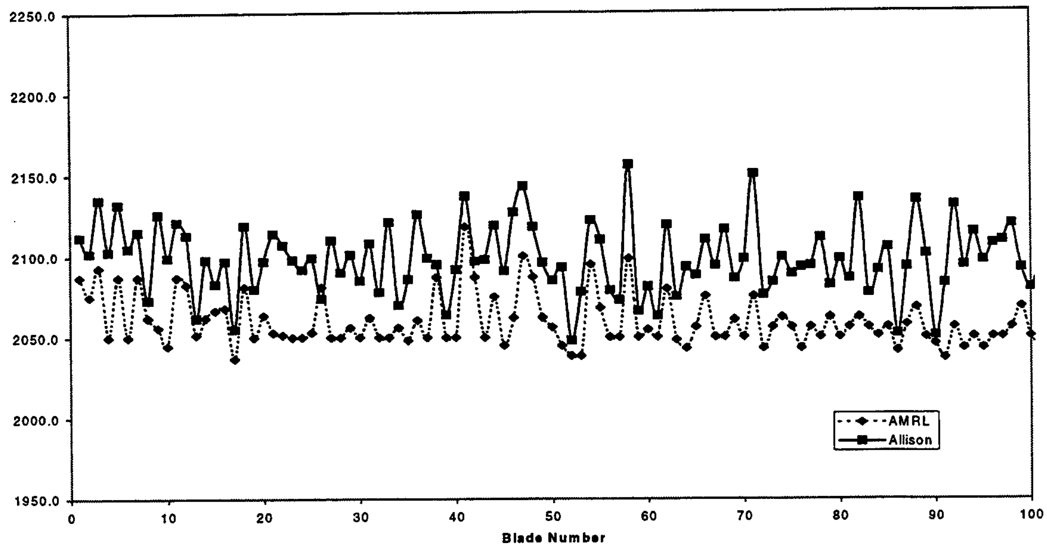

Figure 5. Correlation between AMRL and RRA 1B frequency data (Batch A)

2.4 Final Testing Device

The final testing device was intended for use at Qantas Jet Base in Sydney. In order to alleviate the problems and confusion surrounding the load sharing pin and frequency optimisation carried out by RRA, a new clamping device was designed. This device consisted of an off-the-shelf hydraulic vice manufactured by Enerpac (model VR-4), connected to a small hand pump (model P-142) shown in Figure 6. A set

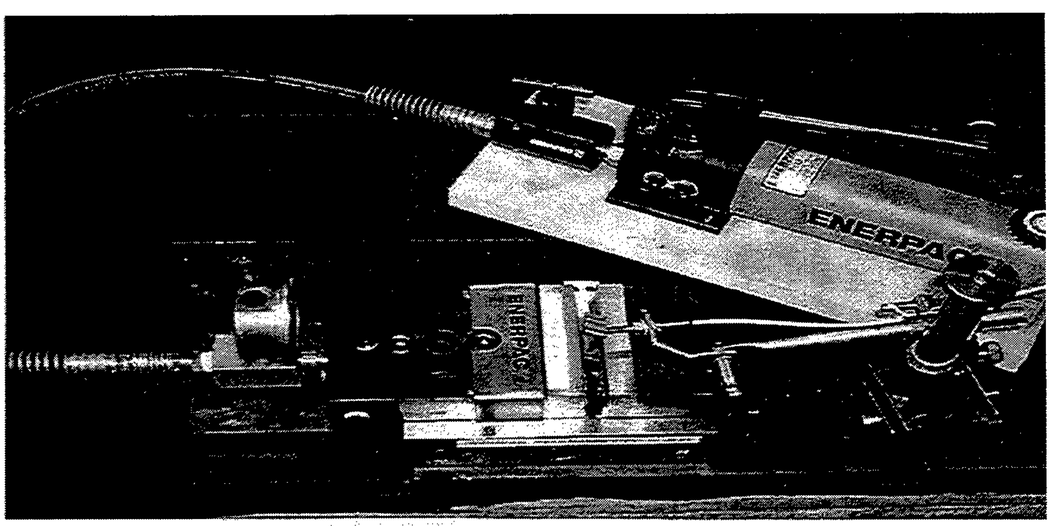

Figure 6. AMRL hydraulic clamping device

of custom machine jaws were manufactured to enable the blade and coupon assembly to be clamped in line with the applied load (Figure 7) thus alleviating the need for a load sharing pin. Additionally, the coupons were adhered to the jaw plates using high strength adhesive Hysol EA 9320. To ensure the coupons were adhered in the correct alignment a blade was lightly clamped in the vice whilst curing. Further modifications included a stop to laterally position the blade in the coupon, and guide bars to further assist alignment of the jaws

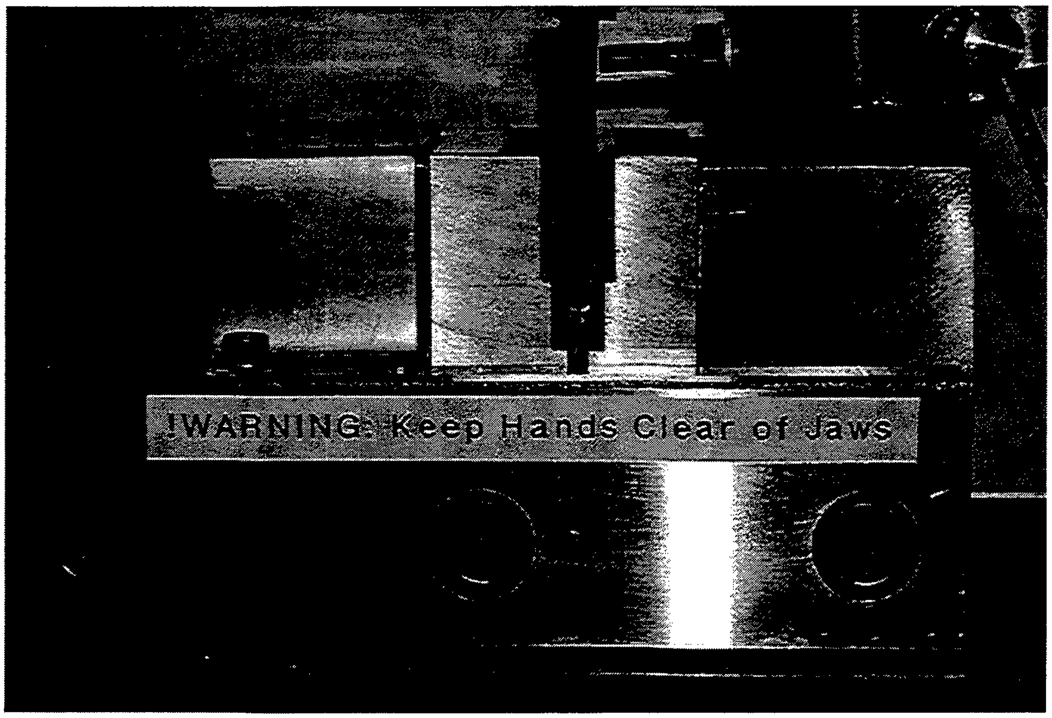

Figure 7. AMRL custom-made vice jaws

3. Free-Free Correlation

Initially it was thought that there would be a correlation between the 1B mode and the first or second free-free mode (blade unrestrained at both ends). If this was the case, testing the blades would be significantly faster, cheaper and the clamping force variable would be removed. The blades were rested on a thin metal frame so that the support locations coincided with the nodes. The support frame was diverging so that the nodes could be found experimentally. After testing a number of batches in both the free-free and 1B modes it was evident that there was little correlation between the two modes (Figure 8). This was primarily due to the 1B mode being predominantly bending, whilst the first and second free-free modes were torsional which was confirmed by the FE model. This testing was not nugatory as it was a valuable source of data for validating the FE model.

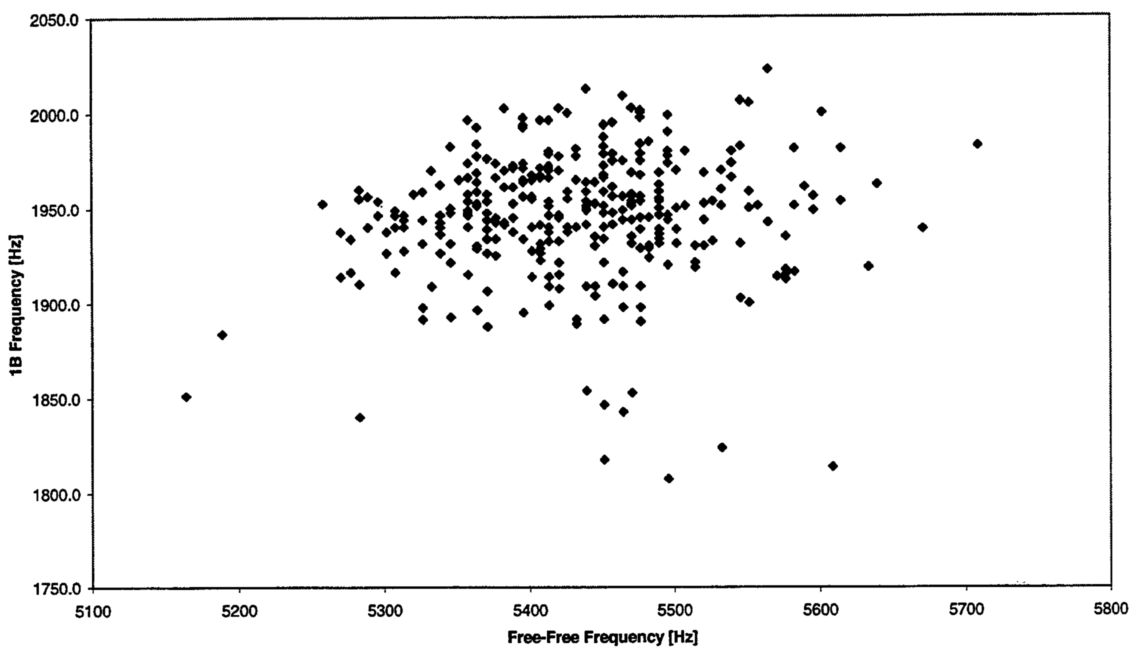

Figure 8. 1B frequency versus free-free (Batch B)

4. Results

4.1 Screening

New blade screening commenced prior to the validation of the AMRL vice. Although it would have been better to commence testing after the vice had been validated, the RAAF required tested blades to be installed in all turbine rebuilds as soon as possible. The testing policy adopted, therefore, was for AMRL to keep all blades that displayed a suspect frequency and to re-test suspect blades in the final validated vice. This ensured that the only blades sent to Qantas for turbine rebuilds were ones that displayed a frequency above the RRA limit of 1850 Hz.

Before the screening apparatus could be commissioned at Qantas, the frequency element of the investigation was terminated at the request of the RAAF. The screening was no longer considered necessary primarily due to the following reasons:

1. Of the 2000 blades tested by AMRL, no blade was found to have a 1B frequency below the RRA limit of 1850 Hz, and
2. Elements of the frequency investigation conducted by AMRL suggested that the initial hypothesis of a frequency initiated failure of the blades was unlikely.

4.2 Double Peaks

Whilst testing the large number of new blades (approximately 2000 blades), it was noted that some blades displayed two peaks less than 50 Hz apart and of similar amplitudes on the frequency display of the FFT analyser. Figure 9 shows both a double frequency peak and a single frequency peak together with the respective time trace. The double peak phenomenon was unable to be explained, however the beat frequency evident in the time domain trace is most likely related. Occasionally a double peak appeared and a predominant peak could not be deciphered (both peaks were approximately the same amplitude); when this was observed, the lower peak was taken as the 1B frequency.

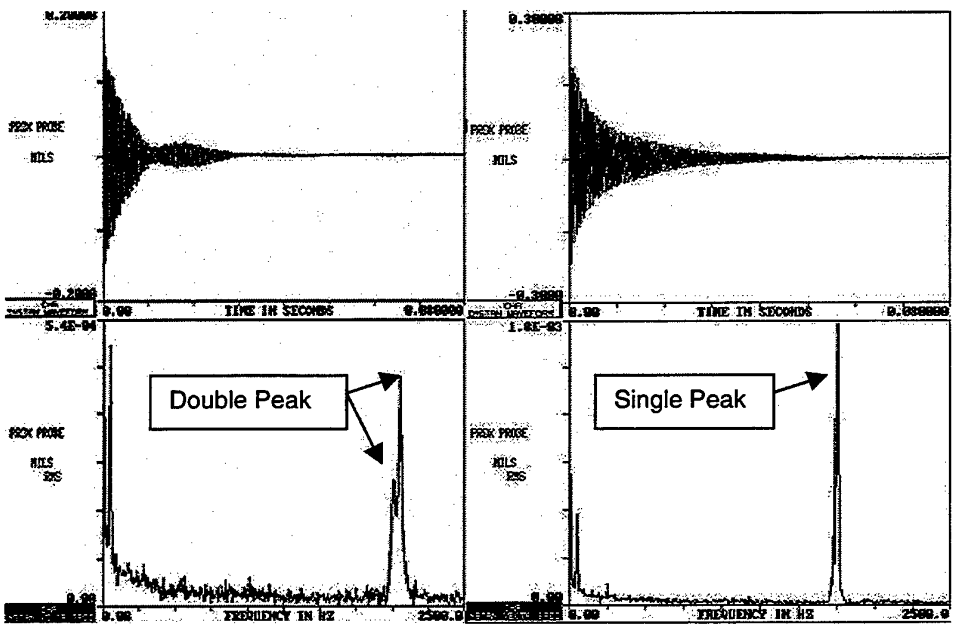

Figure 9. Double frequency peak (left) and single frequency peak (right)

4.3 Blade Untwist

It was suggested by RRA that blade untwist, resulting from creep, may have been a contributing factor to the failure of these blades. In order to verify the significance of untwist on the 1B frequency, an investigation was carried out by AMRL. The results are shown in Table 1. All of the blades used for this investigation were life expired and had a degree of inherent untwist primarily due to creep during service. The blades were further untwisted (incrementally) until the total amount of permanent untwist was approximately double the initial untwist. The degree of untwist was measured using a purpose made RRA jig on loan from Qantas consisting of a blade securing clamp and a dial indicator.

Blade Number	Initial Untwist [inches]	Initial 1B Frequency [Hz]	Final Untwist [inches]	Final 1B Frequency [Hz]
67	0.016	1984	0.030	1996
68	0.018	2040	0.032	2047
69	0.018	2040	0.032	2040
70	0.021	2009	0.035	2003

Table 1. Effect of untwist on blade 1B frequency

The conclusion from this investigation was that untwist by itself does not significantly effect the 1B frequency of first stage blades. Despite this, it was further suggested by RRA that untwist of multiple blades in a turbine disc may allow higher amplitude vibrations to occur thus accelerating HCF [8]. This was unable to be confirmed by the AMRL investigation.

5. Conclusion

This report has discussed the 1B frequency testing of first stage T56-A-7B turbine blades carried out by AMRL for the RAAF. Whilst the exact method used by RRA for frequency testing was not replicated, a new clamping method was developed and correlated. The method of excitation used during this screening was an impact from a light plastic hammer, which then enabled the transient response of the blade to be determined and recorded via an eddy current proximity probe and FFT analyser. It has also been shown that these blades were not overly sensitive to the magnitude of the clamping force above a certain limit. Additionally, it has been shown that for these blades, there was no correlation between the 1B mode and either the first or second free-free modes. The effect of untwist on a blade was investigated and found to have negligible effect on the blades' 1B frequency, however it is possible that untwist allows higher amplitude vibrations to occur. The presence of the double peak phenomenon for a large number of blades has not been adequately explained however this did not appear to be of specific importance to the screening process. Finally, of the 2000 blades tested by AMRL, no blades were found to have a frequency below the stated RRA limit of 1850 Hz.

Acknowledgments

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19. ABSTRACT

Historically it has been difficult to obtain accurate and repeatable frequency data for the first bending mode of turbine blades. This report summarises the technique used by AMRL to screen first stage T56-A-7B turbine blades for the Royal Australian Air Force as part of an investigation into the failure of these blades in service.